Journal of Cleaner Production 201 (2018) 1019–1028

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

# Rethinking packaging production and consumption *vis-à-vis* circular economy: A case study of compostable cassava starch-based material

Fabricio Casarejos [a, e, *], Claudio R. Bastos [b, d], Carlos Rufin [c], Mauricio N. Frota [b]

[a] *Interdisciplinary Center for the Environment, Pontifical Catholic University of Rio de Janeiro, Rua Marquês de São Vicente, n. 225, Gávea, Rio de Janeiro, RJ 22453-900, Brazil*
[b] *Metrology for Quality, Innovation, and Sustainability, Catholic University of Rio de Janeiro, Rua Marquês de São Vicente, n. 225, Gávea, Rio de Janeiro, RJ, 22453-900, Brazil*
[c] *Strategy and International Business Department, Suffolk University, 120 Tremont Street, Suite 370, Boston, MA, 02108, United States*
[d] *CBPAK Technology S/A - Biodegradable Packaging, Rua Vinte de Janeiro, S/N, Área de apoio do aeroporto internacional Galeão, Rio de Janeiro, RJ, 21932-700, Brazil*
[e] *Climate Change Impacts, Adaptation & Modeling Research Group, Center for Ecology, Evolution and Environmental Changes, Faculty of Sciences, Lisbon University, Campo Grande, Lisbon, 1749-016, Portugal*

ARTICLE INFO

*Article history:*
Received 20 February 2018
Received in revised form
11 June 2018
Accepted 12 August 2018
Available online 13 August 2018

*Keywords:*
Circular economy
Packaging
Cassava starch
Sustainability
Climate change
Waste management

ABSTRACT

In the dominant industrial economy, packaging waste represents a significant share of urban solid waste generation (~20.0% by volume in Europe and United States), with wide-ranging negative impacts on interconnected human-Earth systems. The transition from the dominant linear economy to a model grounded in circularity by intention and design can build a new essential foundation for the market economy and packaging utilization. This work examines packaging production and consumption *vis-à-vis* circular economy. In pursuing this goal, it comprises (i) a life cycle inventory analysis of rigid packaging products, discussing yield of raw materials and products, water and energy use, and GHG emissions; (ii) a case study of cassava starch-based material, and (iii) a comparative analysis between petroleum-based and cassava starch-based packaging. The results clearly indicate that compostable packaging of cassava starch has far better societal and environmental outcomes than petroleum-based packaging. The transition from the linear (take-make-use-dispose) to the circular (grow-make-use-restore) pattern creates new opportunities for innovation beyond technology, as it inevitably redefines the significance of waste, products, services, markets, natural capital, and growth. Addressing the GHG emissions from the petroleum-based packaging industry, the societal adoption of bio-based packaging of cassava starch is an effective and promising Climate Change mitigation strategy.

© 2018 Elsevier Ltd. All rights reserved.

## 1. Introduction

To be effective and provide social equity and wellbeing to citizens, sustainable development should be grounded on a transformative, distributive, regenerative, and restorative economic model (Ellen MacArthur Foundation, 2013a, 2013b; Raworth, 2012; UN, 1987). Throughout its evolution and diversification, the dominant industrial economy has gradually based its design and operational processes on one structural characteristic: an open-ended and linear model of resource consumption that follows a take-make-use-dispose systemic pattern (Ellen MacArthur Foundation, 2013b; Ghisellini et al., 2016; McDonough and Braungart, 2002; Raworth, 2017). Industries extract material resources from nature, apply energy and labor to manufacture a product, and sell it to an end consumer, who then discards it when it no longer serves its purposes.

As a result of this *linear economic paradigm*, valuable finite material reserves are irresponsibly being burned or buried in landfills all over the Earth, creating short-term societal prosperity by digging up or cutting down natural resources (Gerst et al., 2014; Ghisellini et al., 2016; Raworth, 2017; Steffen et al., 2011). Additionally, millions of tons of hazardous substances are released into the atmosphere, aquifers, and soil every year, threatening the integrity of biodiversity and increasing risks to human health and

* Corresponding author. Present address: 59 Weston Road, PO BOX 6176, Lincoln, MA, 01773, USA.
*E-mail addresses:* fabricio.casarejos@gmail.com, casarejos@esp.puc-rio.br, casarejos@fc.ul.pt (F. Casarejos), claudio@cbpak.com.br (C.R. Bastos), crufin@suffolk.edu (C. Rufin), frota@esp.puc-rio.br (M.N. Frota).

https://doi.org/10.1016/j.jclepro.2018.08.114
0959-6526/© 2018 Elsevier Ltd. All rights reserved.

wellbeing (Ellen MacArthur Foundation, 2013a; Ghisellini et al., 2016; Steffen et al., 2011; Steffen et al., 2015). If persistent, this paradigm will instigate a myriad of irreversible negative impacts on the Earth systems, disrupting the stability of economies, thereby intensifying inequality and deprivation of essential needs for all (Ellen MacArthur Foundation, 2013a; Rockström et al., 2009; SRC, 2016).

Aiming to provide a better alternative to the dominant linear industrial economy, increasing efforts have been recently dedicated to the development of a transitioning model grounded on a perspective of circularity, known as the Circular Economy (De los Rios and Charnley, 2016; Ellen MacArthur Foundation, 2013a, 2013b; 2014, 2016; Ghisellini et al., 2016; SRC, 2016). Circular Economy refers to an industrial economy model that is transformative, regenerative, and restorative by intention and design (Ellen MacArthur Foundation, 2013a). In line with the Circular Economy concept, material resources are kept in use for as long as possible, reducing drastically the generation of waste, eliminating the use of toxic chemicals, relying on efficient green technologies, and decoupling environmental pressures from economic growth through innovation (Ellen MacArthur Foundation, 2013a, 2013b; McDonough and Braungart, 2002; Huysman et al., 2017).

Circular Economy provides an innovative and coherent conceptual framework to rethink, redesign and restructure the operational mode of the dominant linear industrial economy (Ellen MacArthur Foundation, 2013a, 2013b; SRC, 2016). It offers a challenging opportunity to harness social and technological innovation towards a transformative economy (Ellen MacArthur Foundation, 2016; Raworth, 2017). The Circular Economy approach rests on the following fundamental principles: (1) preserve and enhance natural capital by controlling finite stocks and balancing renewable resource flows; (2) optimize resource yields by circulating products, components, and materials at the highest utility at all times in both technical and biological cycles; and (3) foster system effectiveness by revealing and designing out negative impacts (Ellen MacArthur Foundation, 2013a, 2013b).

In the dominant industrial economy, packaging waste represents a significant share of the urban solid waste generation (~20.0% by volume in Europe and in the United States) (Chen et al., 2016; EC, 2011; Thompson et al., 2009). Currently, packaging materials are mostly petroleum-based synthetic polymers, non-biodegradable and particularly difficult to recycle or reuse considering the mixed levels of contamination and complex composites of their material composition (Davis and Song, 2005). Addressing this issue, recently various bio-based polymers (biodegradable and/or compostable materials) have been increasingly applied in packaging production and applications (Ellen MacArthur Foundation, 2013b; UNEP, 2015). Biodegradable plastic packaging is a promising growth market, projecting a double-digit growth rate by 2019 (Markets and Markets, 2017). Europe and North America are the most important players, accounting for over 65.0% of the global market in 2013 (Markets and Markets, 2017).

In alignment with the basic principles of a Circular Economy, leading businesses and industry groups are improving the design of their products, services, and operational systems (Bastos, 2015; Ellen MacArthur Foundation, 2013b; World Economic Forum, 2017). These initiatives aim to induce the transition of the packaging value chain into a positive value-capturing spiral, with better social, economic and environmental outcomes (Ellen MacArthur Foundation, 2013a). Despite current higher costs compared with their traditional plastic counterparts, many bio-based compostable materials have found increasing commercial packaging applications (such as agricultural products, food, beverages, pharmaceuticals, or personal & home care), creating significant opportunities to increase market-related revenues from compostable packaging materials (Ellen MacArthur Foundation, 2013b; Markets and Markets, 2017; UNEP, 2015). New technological advances have been adopted in the development of bio-based (biomass polymers, e.g., starch, cellulose, lignin, chitin, wool, protein, and DNA) compostable packaging with similar functionality to that of the petroleum-based synthetic polymers (Bohlmann, 2004; Davis and Song, 2005; Ellen MacArthur Foundation, 2013b; UNEP, 2015). The transition from the dominant linear economy to a model grounded on circularity by intention and design can build a new essential foundation for the economy market and utilization of packaging, once it should be inherently biodegradable and compostable.

This work examines packaging production and consumption *vis-à-vis* circular economy. In pursuing this goal, this study encompasses two primary research strands as follows: (i) a case study of compostable cassava starch-based material, comprising a life cycle inventory analysis of raw materials and products yields, water and energy use, and GHG emissions; and (ii) a comparative analysis between petroleum-based and cassava starch-based packaging materials.

## 2. Material and methods

The research approach adopted to examine packaging production and consumption *vis-à-vis* circular economy is structured in the following three stages:

*Literature review*: bibliographic and documentary research was conducted focusing on innovative and cutting-edge initiatives dedicated to foster packaging production and consumption in accordance with the principles of a Circular Economy. Special attention was given to the theoretical approach presented by the Ellen MacArthur Foundation (2013a; 2013b; 2014; 2016), Ghisellini et al. (2016), McDonough and Braungart (2002), Raworth (2017), and SRC (2016). Furthermore, essential concepts, principles, issues, and key-data conveyed by the international organizations and scientific publications cited in this study were identified and processed to substantiate and design this study as a whole.

*Inventory analysis criteria and assumptions*: the performed case study (Section 3.1) focused on the production and consumption of compostable packaging of cassava starch-based material. By means of an inventory analysis, a product packaging life cycle was modeled in line with the perspective of circularity and cradle-to-cradle design thinking (Section 3.1.1, Fig. 1). The inventory analysis aimed to examine the sequential stages in the life cycle of the packaging product. In this context, based on the inventory of key processes and relevant input and output data throughout key stages of the proposed life cycle, raw material and product yields, water and energy use, and GHG emissions were identified and quantified.

The GHG inventory of the stage of *farming* (Section 3.1.2) accounts for the emissions associated to the energy use (diesel) of tractors and trucks in the processes of soil plowing, amendment, seeding, and tending. The average consumption of diesel per hectare was adopted as 75.0 L, which considers a total of 7.5 work hours and an average mileage of 10.0 L per hour. The GHG emission factor was adopted as 2.8 kg $CO_{2eq}$ per liter of diesel consumed (MMA, 2012).

The GHG inventory of the stages of *cassava starch* (Section 3.1.3) and *packaging production* (Section 3.1.4) accounts for the emissions from the energy used (electricity). The GHG emission factor associated with the use of electricity was adopted as 0.09 kg $CO_{2eq}$/kWh (MCTI, 2017).

The total GHG emissions associated with the stage of *compost*

*production* (3.1.6) was quantified considering an average value of 175.0 kg of $CO_{2eq}$ per metric ton of composting material with a carbon to nitrogen ratio ranging from 25.0 to 30.0 (Andersen et al., 2010; Bastos, 2015). The total GHG emissions associated with the stage of *energy recovery* was quantified considering a biogas volumetric concentration of 70.0% of $CH_4$ and 30.0% of $CO_2$ and densities of 0.66 kg/m$^3$ and 1.8 kg/m$^3$, respectively (Cremonez, 2015).

Given that synthetic fertilizer is not used in the farming of cassava crops by the farmers examined in this case study, it was not considered in the inventory analysis. The inventory results for the raw materials and products yields, water and electricity use, and total GHG emissions are summarized in Table 1 (Section 3.1.8).

Regarding GHG emissions for transportation (Section 3.1.8), the average mileage was adopted as 5.52 km per liter of diesel (single axle rack and delivery trucks) and 2.8 kg $CO_{2eq}$ per liter (MMA, 2012). Additionally, the results for $\mathbf{T_{3\text{-}7}}$ and $\mathbf{T_{4\text{-}7}}$ were based on the transportation requirements for a recovery rate of 100.0% (i.e., a scenario in which the total value of GHG emissions associated with transportation is at its maximum level). The inventory results associated with GHG emissions for transportation are summarized in Table 2.

*Data collection and analysis:* the data collection for the performed case study of compostable cassava starch-based material (Section 3.1) was based on the specialized literature (properly cited throughout the main text) and on three complementary sources of actual data made available by the following three manufacturers:

1. *CBPAK Tecnologia S/A - Embalagens Biodegradáveis* (*CPPAK*). Located in the city of Rio de Janeiro, Brazil, *CBPAK* operations are specialized in the production (6.3 metric tons of packaging products/month), distribution, and reverse logistics of compostable cassava starch rigid packaging. The company is a corporate member of the Ellen MacArthur Foundation's Program "Circular Economy 100" (CE 100), which encourages innovative organizations to promote multi-stakeholder collaboration towards an effective implementation of Circular Economy.
2. *Fecularia Bahiamido Serviços Agroindustriais S/A* (*Bahiamido*). Located in the city of Laje, Bahia, Brazil, *Bahiamido* manufactures (6000.0 metric tons/month) modified and non-modified cassava flour and cassava starch.
3. *Vide Verde Compostagem S/A* (*Vide Verde*). Located in the city of Cachoeira de Macacu, Rio de Janeiro, Brazil, *Vide Verde* composts (1500.0 metric tons/month) organic waste. *Vice Verde* is the first compost manufacturer to obtain a license by the Environmental Protection Agency of the State of Rio de Janeiro (INEA) to operate in the reverse logistics of municipal waste.

For these complementary sources, all actual data were formally processed through analysis of official institutional accounting and internal reports, within a 12-month timeframe, from October 2016 to September 2017.

Regarding petroleum-based plastic packaging production and consumption (Section 3.2), the overall data collection was grounded on data available in the specialized technical and scientific literature (properly cited throughout the main text). Particularly, assembling the data collected from Aznalin et al. (2009); Banat and El-Rub (2001); EPA (2015); IFC (2007); Katsoufis (2009); Platts (2015); and Ray et al. (2014), Table 3 summarizes average values of yield, energy and water use, and total GHG emissions associated with plastic packaging production and incineration.

## 3. Results and discussion

### 3.1. Case study of compostable cassava starch-based material

This section presents a conceptual framework for modeling the life cycle of rigid packaging of cassava starch from a perspective of circularity and cradle-to-cradle design thinking. In light of the performed life cycle inventory analysis, this section examines raw materials and product yields, water and energy use, and GHG emissions. The boundaries and general assumptions of the packaging product life cycle system are also described.

#### 3.1.1. Life cycle of rigid packaging of cassava starch

In light of the case study carried out in this work, Fig. 1 depicts the conceptual framework for modeling the life cycle of compostable packaging of cassava starch from a circularity perspective and

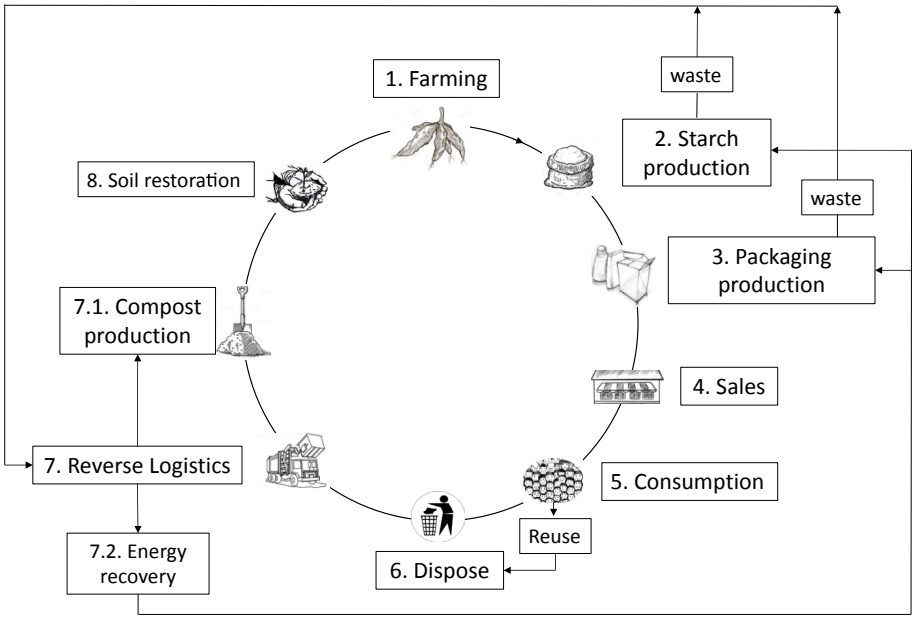


**Fig. 1.** Life cycle of compostable packaging of cassava starch.

cradle-to-cradle design thinking.

*3.1.2. Stage 1: farming cassava crops*

The life cycle of rigid packaging products made of cassava starch begins with the production of raw material through farming cassava crops. The cassava plant (*Manihot esculenta Crantz*) —also known by *manioc*, *yucca*, *aipim*, *macaxeira*, *macamba*— is a perennial *heliophilous* belonging to the *euphorbiaceous* family (FAO, 2013). This is a woody shrub that grows from one to three meters in height, whose tuberous root is rich in starch (Aguiar, 2003). Cassava is cultivated in tropical and sub-tropical regions and is one of the most widely grown root crops in the world (FAO, 2013).

Given its high nutritional value and physical characteristics, cassava is considered a staple food and a multipurpose crop (FAO, 2013). Cassava roots and leaves are prepared into a vast variety of foods according to local traditions and cultures. It is also massively used as feedstuff and wholesome ingredient in the livestock industry (cattle, buffaloes, pigs, chickens, and silkworms). Bitter types of cassava (known as industrial cassava) are especially used for industrial purposes, as they contain cyanogenic glucosides (compounds of cyanide and glucose) and hydrocyanic acid at toxic and poisoning levels (Montagnac et al., 2009).

Since 2000, the world's annual cassava yield has increased by an estimated 100.0 million metric tons (FAO, 2013). In 2014, the world's production of cassava was 268.0 million metric tons, led by Nigeria, the largest producer (47,401,770.0 tons), followed by Thailand (30,227,542.0 tons), Indonesia (23,936,920.0) and Brazil (21,484,218.0) (Worldatlas, 2017).

Cassava crops present a high degree of agro-ecological adaptability, with high tolerance to droughts and poor and acidic soils, thereby not requiring special tending, nor the use of synthetic fertilizer (Bastos, 2015; FAO, 2013). Cassava crops are typically not irrigated and cultivation occurs on lands not well suited to other crops, particularly in marginal lands with unpredictable and low averages of annual rainfall (300.0–400.0 mm) (FAO, 2013; Takahashi and Guerini, 1998). Upon reaching maturity in six or more months after planting, the entire plant is uprooted, and its tuberous root is harvested (Aguiar, 2003; Bastos, 2015). Although the mechanized large-scale farming of cassava crops has recently increased, it is still grown almost exclusively by small-scale farmers using traditional techniques (FAO, 2013). National yields of cassava vary widely depending upon farming methods, population density, soil, and climate conditions (Aguiar, 2003; FAO, 2013). Globally, the highest recorded yield of cassava is 71.0 metric tons per hectare (Montagnac et al., 2009). In Brazil, the average national yield is 13.0 metric tons of cassava roots per hectare (Bastos, 2015).

*3.1.3. Stage 2: Cassava starch production*

Cassava starch is obtained from the tuberous root of cassava crops. Cassava starch presents many remarkable physical characteristics, including: high caloric value, high level of purity, high paste viscosity and clarity, neutral (bland) taste, neutral pH, and high freeze-thaw stability (Bastos, 2015; FAO, 2013; Montagnac et al., 2009). Although cassava starch is primarily used for food purposes, it is also processed into many others products, including pharmaceuticals, paper, textiles, beverages, confectionery, building materials, sweeteners, fuel, and packaging (Bastos, 2015).

Cassava starch production encompasses the following processes: peeling, washing, grading/rasping, mixing with water, filtering/screening, settling, starch washing, dewatering, drying, and milling. Based on *Bahiamido's internal data,* the average yield of cassava starch for each metric ton of cassava root is 275.0 kg. The average values for electricity and water use associated to the production of each metric ton of cassava starch are, respectively, 7218.9 kWh and 4.2 $m^3$. Upon a reverse logistics system, the waste (about 30.0% in weight) from the cassava starch production is then composted (for the purpose of compost production) and/or biodigested (for the purpose of energy recovery).

*3.1.4. Stage 3: packaging production*

Packaging production is developed within an industrial facility, in which a pulp of cassava starch (composed by starch and water) from bitter cassava roots is molded into packaging products. The production system encompasses the following processes: cassava starch pulp preparation, mold filling, pressurized cooking, and mold removal. In the pressurized cooking process, the granules of cassava starch are melted while the cassava starch paste expands inside of the heated mold, thereby shaping it into the desired packaging design. Additionally, for use as a recipient for liquids (such as cups), a hydrophobic and innocuous thin coating is applied.

Based on *CPPAK's internal data*, the average packaging production for each metric ton of cassava starch is 63,334.0 units for cups (at a unit weight of 15.0 g and volume of 200.0 ml); 26,389.0 units for trays (36.0 g weight and 551.0 $cm^2$ area); and 21,110.0 units for both rectangular and cylindrical packages (45.0 g weight and 600.0 ml volume). The average values for electricity and water use associated to the stage of packaging production are, respectively, 2968.3 kWh, and 1.6 $m^3$. Upon a reverse logistics system, the solid waste generated in the packaging production (about 5.0% in weight) is then composting (compost production) and/or biodigested (energy recovery).

*3.1.5. Stages 4, 5, and 6: packaging sales, consumption, and dispose*

The resultant packaging products are sent to the market for sales and societal consumption. The packaging products are sold as services to the consumer, who then returns the used packaging to the producer in exchange for credits for purchasing new packaging. After its use (and possibly reuse) by the end consumer, the used packaging is intentionally disposed for the purpose of reverse logistics (end of life treatment), separately from any other material. Organic residues do not have to be removed and/or washed, as they accelerate the composting and bio-digesting processes. The remaining used packaging that was not recovered by a reverse logistics service is destined for landfilling within a municipal waste management system.

*3.1.6. Stage 7: reverse logistics – compost production and energy recovery*

After its collection by a reverse logistics service, the disposed packaging is destined for the value-extracting cyclical processes of composting (for the purpose of compost production) and biodigesting (for the purpose of energy recovery).

Using traditional composting techniques, the compost production occurs exclusively through an aerobic biological process in which chemical and physical decomposers alter the chemistry and break down cassava starch-based materials into a soil-like and nutrient-rich material (compost), acids, water, and CO2.

Conceptually, packaging materials are considered biodegradable and compostable as long as they continuously decompose into natural elements, fully returning to nature within a reasonably short period of time after disposal (Central Europe, 2012; McDonough and Braungart, 2002; UNEP, 2015). Biodegradation is the partial or complete breakdown of a polymer into $CO_2$, $H_2O$, and biomasses, as a result of a combination of hydrolysis, photodegradation, and microbial activity (McDonough and Braungart, 2002; UNEP, 2015). Compostable materials are a subset of the biodegradable ones; i.e.: those that biodegrade within the biophysical conditions and timeframe of the composting process (McDonough and Braungart, 2002). In this context, compostable

materials are always biodegradable, even though biodegradable materials are not always compostable. Biodegradable materials are compostable only if microorganisms break down their microparticles into a soil-like substance, leading to significant changes in the material's chemical structure (McDonough and Braungart, 2002). Composting is a recycling procedure, an aerobic biological process, in which chemical decomposers (e.g.: bacteria, fungi, actinomycetes) and physical decomposers (e.g.: mites, centipedes, sow bugs, snails, millipedes, springtails, spiders, slugs, beetles, ants, flies, nematodes, flatworms, rotifers, and earthworms) alter the chemistry of, and break down, organic materials into a soil-like and nutrient-rich material (compost), acids, water, and $CO_2$ (Ellen MacArthur Foundation, 2013a; McDonough and Braungart, 2002). Aerobic bacteria are important decomposers, processing a wide variety of organic compounds and providing a highly effective composting process. They consume carbon as a source of energy (by oxidizing organic material), consume nitrogen to produce protein (in order to grow and to reproduce) and excrete plant nutrients such as nitrogen, phosphorus, and magnesium. Physical decomposers are primarily active during the later stages of composting —digging, chewing, sucking, digesting and mixing compostable materials, breaking organic material into smaller pieces, and transforming it into more digestible forms for microorganisms. Their excrement is also digested by bacteria, providing more nutritional value to the compost. Particularly, earthworms are one of the most important of the large physical decomposers in a compost pile, significantly contributing to the compost's nutritional quality. Earthworms ingest and digest organic materials, releasing worm castings, which are rich in plant nutrients such as nitrogen, calcium, magnesium, and phosphorus and hormones, enzymes, and other fermenting substances that continue the breakdown process. Additionally, chemical composition (carbon to nitrogen ratio), aeration, moisture, acidity, temperature, particle size, and pile volume are the primary environmental factors affecting the composting process (Bastos, 2015).

Based on *Vide Verde's internal data*, the compost yield for each metric ton of starch-based materials varies from 200.0 kg to 400.0 kg, within 75–135 days, depending upon biophysical conditions (e.g.: carbon to nitrogen ratio, aeration, moisture, acidity, temperature, particle size, and pile volume) and composting techniques. Generally, the material mixture for composting comprises about three tons of food waste from vegetables for each ton of starch-based materials (with particles size of 2.0 cm or less). Resultant compost with moisture content between 30.0 and 50.0% (in weight) is usually ideal for the composting process and also for handling and soil incorporation.

Alternatively, compostable materials are bio-digested through an aerobic digestion process, producing biogas fuel (mainly $CO_2$ and $CH_4$) and a nutrient-rich, sterile, organic sludge. In this context, the produced biogas is collected and used directly as a fuel for cooking, heating, and electricity production, and the nutrient-rich organic sludge applied as a fertilizer (Bastos, 2015; Cremonez, 2015). In the anaerobic digestion process, organic materials are broken down (biochemically digested) by microorganisms (e.g.: bacteria and archaea) in an anoxic environment. Biogas digesters represent an efficient potential source of energy (Cremonez, 2015). However, not all compostable materials are valuable resources for an efficient bio-digesting process. Many and diverse are the factors that influence the overall nature and speed of the bio-digesting process, including chemical composition (carbon to nitrogen ratio), pH, temperature, particle size, and organic loading rate (frequency and speed at which the substrate is added to the digester) (Cremonez, 2015).

According to Cremonez (2015), the energy recovery yield for each ton of starch-based materials varies from 800.0 to 1200.0 $m^3$ of biogas and from 1144.0 to 1716.0 kWh of electricity of per ton of starch-based materials. The biogas yield depends upon the physical conditions of the bio-digesting process, including bio-digester technology, organic material composition, temperature, and microbiological characteristics. Comparatively to other organic materials (e.g.: sugar cane, corn, wood), cassava starch materials present a high degree of biodegradability (short time in the bio-digesting process) and a high concentration of methane in the biogas (containing from 60.0% to 70.0% in volume) (Cremonez, 2015).

#### 3.1.7. Stage 8: soil amendment and restoration

Closing the cradle-to-cradle cycle, the recovered energy returns to the cassava starch production and/or packaging production and the resultant compost is readily applied for soil restoration to the growing of new cassava crops. The incorporation of compost to the soil improves its nutritious content, microbial activity, pH, drainage and water holding capacity, and structure (by reducing surface crusting and compaction). Once the soil is continuously restored and its health is improved, increasing yields of cassava crops with better quality of cassava plants at a lower farming cost is potentially obtained. Additionally, heathier soils are significantly less subject to weed infestations, pests, and diseases.

Based on *Vide Verde's internal data*, the compost yield for purposes of soil restoration of cassava crops varies from 0.5 to 1.0 kg per cassava plant, depending upon the soil and climate conditions. Note that this is equivalent to a range of 5.0–10.0 metric tons per hectare for a typical population density of 10,000 plants.

#### 3.1.8. Compilation of inventory results

Compiling relevant input and output data from key-processes discussed in sections 3.1.1 to 3.1.7, Table 1 summarizes the inventory results for the average yield of raw materials and products, water and electricity use, and total GHG emissions per metric ton of compostable packaging of cassava starch. To establish a baseline for comparison, the total value of energy use per metric ton of packaging product is accounted for in terms of equivalent units. Following this procedure, 75.0 L of diesel is equivalent to 651.1 kWh. The GHGs released during the composting and bio-digesting processes are categorized as biogenic emissions that recirculate in a short period of time into the cradle-to-cradle lifecycle.

Transportation is commonly related to all stages of the packaging life cycle and its requirements vary widely depending upon the distances between each stage and shipping systems of materials and products. Aiming to estimate the total GHG emission in the particular context of the proposed case study, the transportation boundary system accounts for:

- **$T_{1-2}$**: transferring cassava roots from the farm field to the starch manufacturer;
- **$T_{2-3}$**: delivering cassava starch from the starch manufacturer to the packaging production facility;
- **$T_{3-4}$**: distributing packaging products from the packaging production facility to the costumer;
- **$T_{2-7}$**: performing the reverse logistics of waste from the starch manufacturer to the composting and bio-digesting facility,
- **$T_{3-7}$**: performing the reverse logistics of solid waste from the packaging production facility to the composting and bio-digesting facility;
- **$T_{4-7}$**: performing the reverse logistics of disposed packaging from the sales customer to the composting and bio-digesting facility.

The inventory results of the GHG emissions for transportation

**Table 1**
Inventory results for average yield, water and energy use, and total GHG emission.

| Life cycle stage | Average values per metric ton of compostable packaging of cassava starch | | | |
|---|---|---|---|---|
| | Yields of raw material and products | Energy use | Water use ($m^3$) | GHG emission (Kg $CO_{2eq}$) |
| 1 | 3.63 metric tons of cassava roots per 2792.3 $m^2$ | 75.0 L of diesel (or 651.1 kWh) | Not irrigated | 58.6 |
| 2 | 1.05 metric ton of starch per 3.63 metric tons of peeled fresh cassava roots | 7218.9 kWh | 4.2 | 649.7 |
| 3 | 1.00 metric ton of packaging per 1.05 metric tons cassava of starch | 2968.7 kWh | 1.6 | 267.2 |
| 7 | 0.3 metric tons of compost per metric ton of cassava materials within 75–135 days | Biogenic | N/A | 175.0 |
| | 1050.0 $m^3$ of biogas yielding 1501.5 kWh of electricity per metric ton of cassava starch materials | Biogenic | N/A | 928.6 |
| 8 | 2.1 metric tons of compost per 2792.3 $m^2$ | Accounted for in stage 1 | Not irrigated | Accounted for in stage 1 |
| **Total value per metric ton of packaging product** | | **10,838.7 kWh** | **5.8** | **2020.5** |

are summarized in Table 2.

Compiling the results summarized in Tables 1 and 2, the total GHG emissions associated with the production and consumption of compostable packaging of cassava starch are estimated at 2022.0 kg $CO_{2eq}$ per metric ton of packaging product. Although an ideal scenario of 100.0% recovery rate is assumed, the GHG emissions associated with transportation are insignificant (0.2%) in comparison with the total GHG emissions associated with the production of compostable packaging of cassava starch. Note that more realistic scenarios of recovery rate (e.g.: from 10.0 to 25.0%, see Bastos, 2015) imply even smaller values of GHG emissions associated to the stage 7 (compost production and energy recovery) and transportation.

Furthermore, it is well-known that cassava plants capture $CO_2$ from the atmosphere in their process of biomass formation. The total amount of $CO_2$ captured by cassava plants for each metric ton of cassava root is 915.0 kg, which is calculated for a carbon concentration of 250.0 kg (i.e., 25.0%) per metric ton of cassava root (Bastos, 2015) and a molar mass ratio of $CO_2 : C = 3.66$. Given that 3.63 metric tons of cassava roots are needed to produce one ton of packaging product, the total amount of $CO_2$ captured per metric ton of packaging product is calculated to be 3321.5 kg. Summing up these results, the resulting total amount of $CO_2$ captured is estimated at 1299.5 kg per metric ton of packaging product.

Accounting for the energy used in stages 1, 2 and 3 and the energy recovered from the reverse logistics of starch-based materials (Table 2), the total electricity used per metric ton of packaging product is calculated to equal 8908.2 kWh. In this case, the amount of bio-digested starch-based materials comprises one metric ton of disposed packaging and 350.0 kg of waste from the cassava starch and packaging production (i.e., the waste recovery rate is considered to be 100.0%). Additionally, the total water required to produce one metric ton of starch-based packaging products is estimated at 5.8 $m^3$.

### 3.2. Comparative analysis

In light of the results discussed in Section 3.1, this section presents a comparative analysis between petroleum-based and cassava starch-based packaging materials. For the petroleum-based materials all data collection is obtained from the specialized literature.

Contrasting the circular life cycle of compostable packaging of cassava starch (depicted in Fig. 1), the dominant plastic packaging production and consumption is grounded in the linear pattern of take-make-use-dispose of non-compostable materials (Ellen MacArthur Foundation, 2013a, 2013b; EPA, 2015). Fig. 2 depicts the dominant plastic packaging production and consumption structured into five broad life cycle stages: *Material extraction* (encompassing petroleum exploration, extraction, and refining); *Production* (including production of synthetic polymers and packaging); *Consumption* (considering use and reuse); *Disposal*; and *Waste Management* (comprising recycling, energy recovery, and landfilling).

Plastic packaging is inexpensive, lightweight, strong and, especially, long-lasting (Thompson et al., 2009). It is predominantly (over 95.0%) manufactured from petroleum-based synthetic polymers (American Chemistry Council, 2013; Bohlmann, 2004). About 8.0% of the world's total petroleum is used to produce plastic and to power plastic manufacturing processes (American Chemistry Council, 2013). The life cycle of plastic packaging products begins with the processes of petroleum exploration, extraction, and refining in order to obtain naphtha, the primary feedstock. The average yield of naphtha per metric ton of petroleum is 300.0 kg (Centre for Industry Education Collaboration, 2016). Petroleum-based synthetic polymers are then produced from secondary feedstocks obtained through the cracking process of naphtha (IFC, 2007). These polymers are subsequently transformed into rigid plastic packaging products through a variety of industrial methods, including extrusion, blow molding, thermoforming, and injection molding (American Chemistry Council, 2013; EPA, 2015). The main

**Table 2**
Inventory results of the GHG emissions for transportation.

| Transportation Steps | Raw materials or products (kg/year) | Transportation requirements | | GHG emission kg $CO_{2eq}$/year |
|---|---|---|---|---|
| | | Distance (km/year) | Fossil fuel (liters/year) | |
| $T_{1-2}$ | 288,600.0 | 1150.0 | 208.3 | 583.2 |
| $T_{2-3}$ | 79,400.0 | 4308.0 | 780.4 | 2185.1 |
| $T_{3-4}$ | 75,600.0 | 250,200.0 | 45,326.1 | 126,913.1 |
| $T_{2-7}$ | 209,200.0 | 2988.5 | 541.4 | 1515.9 |
| $T_{3-7}$ | 3800.0 | 2026.6 | 367.1 | 1027.8 |
| $T_{4-7}$ | 75,600.0 | 40,320.0 | 7304.3 | 20,452.0 |
| **Total** | **732,200.0** | **300,933.1** | **54,527.6** | **152,677.1** |
| **Total GHG emission per ton of packaging product** | | | | **2.02 kg** |

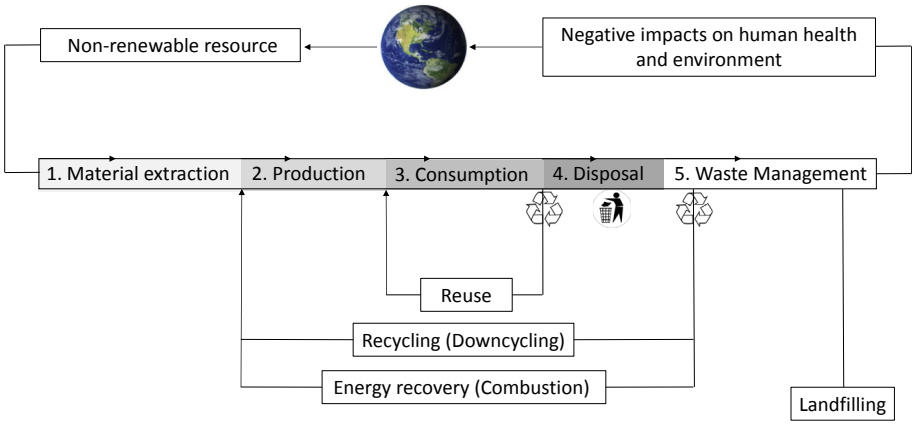


**Fig. 2.** Life cycle of the dominant plastic packaging production and consumption.

synthetic polymers used for the manufacturing of plastic packaging are High-Density Polyethylene (HDPE), Low-Density Polyethylene (LDPE), polyethylene terephthalate (PET), linear low-density polyethylene (LLDPE), polypropylene (PP), general purpose polystyrene (PS), and polyvinyl chloride (PVC) (EPA, 2015; IFC, 2007). Ethylene and propylene are the main constituents of rigid packaging polymers, with an average yield of 300.0 kg and 325.0 kg per metric ton of naphtha, respectively (Ray et al., 2014; Aznalin et al., 2009). Ethylene is also used to produce styrene and vinyl chloride, with average yields of 290.0 kg and 490.0 kg, respectively, per metric ton of ethylene (Platts, 2015).

The global consumption of plastic packaging has grown exponentially since it was heavily adopted by industry in the 1950s (Plastics Europe, 2015; Worldwatch Institute, 2015). About 78.0 million metric tons of plastic packaging are produced per year (World Economic Forum, 2017; UNEP, 2014). Plastic packaging accounted for over 30.0% of packaging sales in 2009 (World Packaging Organization, 2009) and packaging production accounts for over 35.0% of sales and use of thermoplastic resins in 2014 (Worldwatch Institute, 2015). Packaging waste represents a significant share of municipal solid waste generation in developed economies (Ellen MacArthur Foundation, 2013b). The annual packaging waste generation per capita was estimated at 235.0 kg in the United States in 2012 (EPA, 2014) and 160.0 kg in Europe in 2013 (EC, 2016), encompassing 20.0% (in volume) of the total municipal solid waste generation in both regions (EPA, 2014; EC, 2016, 2017). Little is known about the plastic packaging waste in developing and emerging economies. It is a major concern, considering that their waste management infrastructure may not be developing at an appropriate rate to deal with their increasing levels of packaging waste generation (Thompson et al., 2009; UNEP, 2015).

Given the severe impacts of packaging waste, it has become a leading concern among local and global environmental issues, including the erosion of natural habitats; disruption of wildlife biodiversity through ingestion and entanglement in plastic (principally in marine environments); and pollution by releasing toxic contaminants into the air, soil, and water (EC, 2011; Rockström et al., 2009; Steffen et al., 2011, 2015; Thompson et al., 2009; World Economic Forum, 2017). Most plastic packaging is used only once and 95.0% of its value – estimated at 80.0–120.0 billion dollars annually – is lost to the global economy after its initial use (World Economic Forum, 2017). Plastic packaging is difficult to recycle due to mixed levels of contamination and complex composites (Davis and Song, 2005). The waste from plastic packaging exhibits one of the lowest reuse and recycling rates (Ellen MacArthur Foundation, 2013b) and highest lack of proper disposal procedures (EPA, 2014; Plastics Europe, 2015; Worldwatch Institute, 2015). The vast majority (over 80.0%) of the disposed packaging is accumulating in landfills or sloughing off in the natural environment as litter (Geyer et al., 2017). Upon recovery, disposed packaging is alternatively converted by combustion (incineration in waste-to-energy facilities) into ash, gas fuel, and heat, or downcycled to replace products of lesser quality and lower recycling rates (Mugdal et al., 2011). Both the combustion and downcycling processes are highly polluting, adding more GHGs into the atmosphere and harmful contaminants (e.g., toxins, heavy metals) into the overall Earth systems (Ellen MacArthur Foundation, 2013a, 2013b; McDonough and Braungart, 2002).

Assembling the data collected from Aznalin et al. (2009); Banat and El-Rub (2001); EPA (2015); IFC (2007); Katsoufis (2009); Platts (2015); and Ray et al. (2014), Table 3 summarizes average values of yield, energy and water use, and total GHG emissions associated with plastic packaging production and incineration (for the purpose of energy recovery). For the production of synthetic polymers, the results include the processes of petroleum extraction and refining, and naphtha cracking. For the production of plastic packaging, the results encompass emissions from the energy used (electricity) for the extrusion and molding of the packaging products (Bastos, 2015; EPA, 2015). Given that the water use for plastic packaging production is not significant when compared to the total water use associated with petroleum extraction, refining, and naphtha cracking processes (EPA, 2015), it is not considered in the analysis carried out in this study.

Assembling the results summarized in Table 3, the average values of energy use required to produce one metric ton of plastic packaging product vary from 7466.0 kWh (for the polymer LLDPE) to 11,624.0 kWh (for PS). Alternatively, if energy recovery is considered at an ideal waste recovery rate of 100.0%, this value range varies from 5172.0 kWh (for LLDPE) to 9554.0 kWh (for PS). The average values of water use to produce one metric ton of plastic packaging product vary from 14.2 $m^3$ (for LLDPE) to 51.8 $m^3$ (for PS). The average values of total GHG emissions per metric ton of plastic packaging vary from 1521.0 kg $CO_{2eq}$ (for PP) to 2557.0 kg $CO_{2eq}$ (for PS). If energy recovery (through combustion) is considered at an ideal waste recovery rate of 100.0%, the average values of total GHG emissions per metric ton of plastic packaging vary from 2722.0 kg $CO_{2eq}$ (for PVC) to 4332.0 kg $CO_{2eq}$ (for PS).

Focusing on the results for energy use, water use, and GHG emissions, the following paragraphs discuss the main outcomes obtained from the overall data collection and life cycle inventory analysis performed in this work.

The **energy use** requirements of compostable packaging of

**Table 3**
Average values of yield, energy and water use, and total GHG emissions associated to plastic packaging production and incineration.

| Synthetic Polymers | Production | | | | Incineration | |
|---|---|---|---|---|---|---|
| | Yields | Energy use (kWh/metric ton) | Water use ($m^3$/metric ton) | GHG emissions (Kg $CO_{2eq}$/metric ton) | Energy recovery (kWh/metric ton) | GHG emissions (Kg $CO_{2eq}$/metric ton) |
| HDPE | 1.0 metric ton per 0.95 metric ton of ethylene | 7666.0 | 14.9 | 1532.0 | 2300.0 | 1367.0 |
| LDPE | 1.0 metric ton per 0.97 metric ton of ethylene | 9001.0 | 15.0 | 1775.0 | 2289.0 | 1367.0 |
| PET | 1.0 metric ton per 0.83 metric ton of ethylene | 9185.0 | 24.2 | 2359.0 | 1219.0 | 1334.0 |
| LLDPE | 1.0 metric ton per 0.96 metric ton of ethylene | 7466.0 | 14.2 | 1532.0 | 2294.0 | 1367.0 |
| PP | 1.0 metric ton per 0.98 metric ton of propylene | 7663.0 | 15.4 | 1521.0 | 2294.0 | 1367.0 |
| PS | 1.0 metric ton per 1.05 metric tons of styrene | 11,624.0 | 51.8 | 2557.0 | 2070.0 | 1775.0 |
| PVC | 1.0 metric ton per 0.97 metric ton vinyl chloride | 9831.0 | 31.1 | 2017.0 | 909.0 | 705.0 |
| Packaging products | 1.0 metric ton per metric ton of polymer | 901.0 | Not quantified | 676.0 | | |

cassava starch (estimated as 8908.2 kWh) presents a slight difference when compared to plastic packaging, for which the estimated average energy use considering all listed polymers and energy recovery values is 7008.7 kWh. However, if energy recovery is not considered, the resulting average energy use considering all listed polymers is 9819.4 kWh. The energy recovery potential of compostable packaging of cassava starch (average of 2002.0 kWh of electricity of per ton of starch-based materials) is slightly higher when compared to plastic packaging, for which the average energy recovery considering all listed polymers is 1910.7 kWh per ton of waste. Regardless of this slight difference, it is crucial to take into account that starch-based materials are specifically designed to be safely bio-digested in the energy recovery stage. Although some plastic materials can be safely burned (e.g.: oxobiodegradable polyolefin), the dominant petroleum-based synthetic polymers are not designed to be harmlessly incinerated, as they release toxic substances (e.g.: dioxins, heavy metals and chemicals, such as cadmium, mercury, sulfuric acid and hydrogen chloride) and bioaccumulate in the overall Earth systems, thus producing potentially harmful effects. The combustion of plastic packaging waste is an outdated and ineffective waste reduction and waste-to-energy strategy that does not address the social and environmental impacts of pollution in the first place.

The inventory results clearly indicate that the **water use** required to produce plastic packaging products far exceeds the total water use required to produce starch-based ones. As discussed in Section 4.1, the average water use required to produce one metric ton of synthetic polymer varies from 14.2 $m^3$ (LLDPE) to 51.8 $m^3$ (PS) per metric ton of plastic packaging product. The quantified water use for starch-based products is exclusively due to the production of the secondary feedstock (cassava starch) and packaging products, estimated as 5.8 $m^3$ per metric ton of packaging products. In the context of primary feedstock production, cassava crops present a null water use, as they are characteristically not irrigated. Additionally, cassava crops are cultivated in marginal lands with traditional farming techniques, thereby exhibiting insignificant land use impacts. By contrast, in order to obtain Naphtha and synthetic polymers, the processes of petroleum extraction, refining, and cracking are highly water intensive and environmentally disruptive.

The **GHG emissions**, in comparison with plastic packaging, compostable packaging of cassava starch is clearly favorable, exhibiting a net $CO_2$ capture potential of 1299.5 kg per metric ton of packaging product. By contrast, plastic packaging presents a total value of $CO_{2eq}$ emissions varying from 1521.0 kg $CO_{2eq}$ (for not incinerated PP) to 2557.0 kg $CO_{2eq}$ (for not incinerated PS) and 2722.0 kg $CO_{2eq}$ (for incinerated PVC) to 4332.0 kg $CO_{2eq}$ (for incinerated PS) per metric ton of packaging product. For a global production of 78.0 million metric tons of plastic packaging per year (as discussed in Section 3.1), the associated GHG emissions present a value range varying from 118.6 (for not incinerated PP) to 199.4 (for not incinerated PS) and 212.3 (for incinerated PVC) to 337.8 (for incinerated PS) million metric tons of CO2eq/year. By contrast, considering an equal scenario of global production for the compostable packaging of cassava starch, the resulting net $CO_2$ capture potential is 118.6 million metric tons per year.

## 4. Final remarks

The pursuit of effective Circular Economy applied to packaging production and consumption calls for a new participatory arrangement between businesses and customers built on a holistic perspective of a product's social value and physical performance. This implies the need for the adoption of cleaner productive systems at an institutional level and consumers' awareness and proactivity at an individual level. Managers and consumers are confronted with day-to-day issues associated with social and ecological systems that are not independent from one another, but dynamically integrated with one another.

The transition from the linear (take-make-use-dispose) to the circular pattern (grow-make-use-restore) opens up new opportunities for innovation beyond technology, while redefining the conceptual meaning of waste, products, services, markets, natural capital, and growth. This leads to substantial social, economic, and environmental benefits, adapting communities to behavioral adjustments associated with new ways of living. Additionally, this also establishes an ambitious societal goal of decoupling the packaging market from the fossil fuels industry through innovation and social engagement and eco-responsibility. The implementation of a packaging production and consumption system within a perspective of circularity and cradle-to-cradle design thinking unburdens individuals and communities from the malpractice of landfilling (or downcycling) finite resources. The full circularity inherited from the proposed cradle-to-cradle design goes far beyond the mechanistic and reductionist approach of the dominant packaging production and consumption.

Given that bio-based compostable packaging is produced from renewable natural resources (raw materials from crops), if properly designed under a perspective of circularity and managed in alignment with sustainable development principles, this alternative packaging would significantly reduce environmental impacts and disposal costs. Additionally, its adoption could establish an uninterrupted circular cycle, injecting valuable biological nutrients into circular paths, promoting soil fertility restoration and regeneration, and increasing harvests. The cyclical transformations intrinsic to the cradle-to-cradle biological metabolism sustain the material's physical significance. Along this line of thought, the concept of waste would lose its dominant meaning since the packaging products are intentionally designed to fit within a biological material cycle.

To align with the Circular Economy mind-set, business models must be structurally reconfigured around the servitization of societal and environmental solutions and values rather than the "business as usual" product sales. Compostable packaging of cassava starch is designed to fully return to the biological metabolism of the natural world. Instead of considering packaging as products to be purchased, owned, and disposed of by consumers, packaging products must be reconceived as services. In other words, packaging products must be sold as services to the consumer, who then returns the used packaging to the producer in exchange for credits for purchasing new packaging.

Even though cassava starch packaging products typically require more raw material than their counterpart for plastic packaging, the recovered cassava starch-based material is composted and biodigested, thereby fostering raw material and energy resources, while replacing the concept of end-of-life for restoration and regeneration. While the cost of the reverse logistics service is included in the sale price of the packaging product, the gains incurred are deducted from it as well. In this sharing financial arrangement, the consumer purchases the service for a finite period of time and do not pay for the ownership of the packaging material that are ordinarily useless for them after the product's functional life.

## 5. Conclusions

Compostable materials have the potential to solve a variety of waste management issues regarding disposable packaging. Given the compostability and innocuity of cassava starch, it does not require constant monitoring by current and future generations, thus considerably reducing waste management costs and needs for complex regulatory frameworks and bureaucracy.

Considering its low energy and water use, land use impacts, and $CO_2$ capture potential, it is clear that the production and consumption of compostable bio-based packaging of cassava starch has far better environmental outcomes than plastic packaging. Addressing the GHG emissions from the petroleum-based packaging industry, the societal adoption of compostable packaging of cassava starch within a cradle-to-cradle design thinking is an effective and promising Climate Change mitigation strategy.

The circular economy of compostable packaging of cassava starch also presents many economic, social and cultural benefits, positively recoupling economic development growth and social-ecological resilience. Compared to other starches, the cassava starch production requires low infrastructure, which allows small-scale producers with limited financial capacity to operate in the market, potentially increasing local jobs and wealth distribution, empowering the culture of family farms, and enhancing reverse logistics systems. Additionally, it would certainly boost societal awareness regarding environmental issues and public health safety, engaging individuals and communities to take urgent action and to make informed and responsible decisions.

## Acknowledgments

The authors would like to acknowledge the Foundation for Science and Technology of the State of Rio de Janeiro (FAPERJ-PDS: 200026/2016) for the financial support of the first author. They would also like to thank all managers at "*CBPAK Tecnologia S/A – Embalagens Biodegradáveis*", "*Fecularia Bahiamido Serviços Agro-industriais S/A*", and "*Vide Verde Compostagem S/A*" for their engagement and participation in the data collection part of this study. The second author is also grateful to Pontifical Catholic University of Rio de Janeiro for sponsoring his Master Course in *Metrology for Quality, Innovation, and Sustainability*.

## References

Aguiar, E.B., 2003. Produção e qualidade de raízes de mandioca de mesa (Manihot esculenta Crantz) em diferentes densidades populacionais e épocas de colheita. Master Thesis. Instituto Agronômico de Campinas, São Paulo, Brazil, pp. 1–101.

American Chemistry Council, 2013. Economics and Statistics Department, Plastic Resins in the United States, Washington, DC.

Andersen, J.K., Boldrin, A., Christensen, T.H., Scheutz, C., 2010. Greenhouse gas emissions from home composting of organic household waste. Waste Manag. 12, 2475–2482. https://doi.org/10.1016/j.wasman.2010.07.004.

Aznalin, R.R., Arslanov, M.M., Akhmetov, A.F., Balyanov, A.G., 2009. Refinery Technological Processes Integration. Propylene Production on FCC Unit. Oil & Gas Business, p. 1.

Banat, Y., El-Rub, Z.A., 2001. A Technical and Economic Feasibility Study of: Production of Polyethylene Terephthalate by Direct Esterification Using Pervaporation. University of Twente, Faculty of Chemical Technology, Enschede.

Bastos, C.R., 2015. Embalagens compostáveis: uma estratégia para a redução de impacto ambiental. Master Thesis. Pontifical Catholic University of Rio de Janeiro, Rio de Janeiro, Brazil, pp. 1–93.

Bohlmann, G.M., 2004. Biodegradable packaging life-cycle assessment. Environ. Prog. 23 (4), 342–346.

Central Europe, 2012. Certification of Biodegradable Plastics. Innovative Value Chain Development for Sustainable Plastics in Central Europe (PLASTiCE). http://www.plastice.org/fileadmin/files/Certification_biodegradable_Plastics_V2marec.pdf. (Accessed 9 March 2017).

Centre for Industry Education Collaboration, 2016. The Essential Chemical Industry-online: Distillation. In: http://www.essentialchemicalindustry.org/processes/distillation.html#distillation. (Accessed 17 December 2017).

Chen, L., Pelton, R.E.O., Smith, T.M., 2016. Comparative life cycle assessment of fossil and bio-based polyethylene terephthalate (PET) bottles. J. Clean. Prod. 137, 667–676.

Cremonez, P.A., 2015. Digestão anaeróbia de polímero orgânico à base de fécula de mandioca. Master Thesis. Universidade Estadual do Oeste do Paraná, Paraná, Brazil, pp. 1–98.

Davis, G., Song, J.H., 2005. Biodegradable packaging based on raw materials from crops and their impact on waste management. Ind. Crop. Prod. 4873, 1–15.

De los Rios, I.C., Charnley, F.J.S., 2016. Skills and capabilities for a sustainable and circular economy: the changing role of design. J. Clean. Prod. xxx, 1–14.

Ellen MacArthur Foundation, 2013a. In: Towards the Circular Economy – Economic and Business Rationale for an Accelerated Transition, vol. 1. https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Ellen-MacArthur-Foundation-Towards-the-Circular-Economy-vol.1.pdf. (Accessed 10 December 2017).

Ellen MacArthur Foundation, 2013b. In: Towards the Circular Economy – Opportunities for the Consumer Goods Sector, vol. 2. https://www.ellenmacarthurfoundation.org/publications/towards-the-circular-economy-vol-2-opportunities-for-the-consumer-goods-sector. (Accessed 12 December 2016).

Ellen MacArthur Foundation, 2014. Towards the Circular Economy – Accelerating the Scale-up across Global Supply Chains, vol. 3. https://www.ellenmacarthurfoundation.org/publications/towards-the-circular-economy-vol-3-accelerating-the-scale-up-across-global-supply-chains. (Accessed 12 December 2016).

Ellen MacArthur Foundation, 2016. Intelligent Assets: Unlocking the Circular Economy Potential. https://www.ellenmacarthurfoundation.org/publications/intelligent-assets. (Accessed 12 December 2016).

Environmental Protection Agency (EPA), 2014. Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2012. https://www.epa.gov/sites/production/files/2015-09/documents/2012_msw_fs.pdf. (Accessed 2 March 2017).

Environmental Protection Agency (EPA), 2015. Waste Reduction Model (WARM) Version 13. https://www3.epa.gov/epawaste/conserve/tools/warm/pdfs/Plastics.pdf. (Accessed 17 December 2017).

European Commission (EC), 2011. Science for Environment Policy - in Depth Report. Plastic Waste: Ecological and Human Health Impacts. http://ec.europa.eu/environment/integration/research/newsalert/pdf/IR1_en.pdf. (Accessed 2 March 2017).

European Commission (EC), 2016. EUROSTAT Statistics Explained - Packaging Waste Statistics. http://ec.europa.eu/eurostat/statistics-explained/index.php/Packaging_waste_statistics. (Accessed 2 March 2017).

European Commission (EC), 2017. EUROSTAT Statistics Explained - Municipal Waste Statistics. http://ec.europa.eu/eurostat/statistics-explained/index.php/Packaging_waste_statistics. (Accessed 3 March 2017).

Food and Agriculture Organization of the United Nations (FAO), 2013. Save and Grow Cassava - a Guide to Sustainable Production Intensification. http://www.fao.org/3/a-i3278e.pdf. (Accessed 10 October 2017).

Gerst, M.D., Rakin, P.D., Rockström, J., 2014. Contours of a resilient global future. Sustainability 6, 123–135.

Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. J. Sci. Adv. 3 (7). https://doi.org/10.1126/sciadv.1700782.

Ghisellini, P., Cialani, C., Ulgiati, S., 2016. A review on circular economy: the expected transition to a balanced interplay of environmental and economic

systems. J. Clean. Prod. 114, 11–32.
Huysman, S., Schaepmeester, J.D., Ragaert, K., Dewulf, J., Meester, S.D., 2017. Performance indicators for a circular economy: a case study on post-industrial plastic waste. Resour. Conserv. Recycl. 120, 46–54.
International Finance Corporation (IFC), 2007. Environmental, Health, and Safety Guidelines: Petroleum-based Polymers Manufacturing. http://www.ifc.org/wps/wcm/connect/c8fd2d0048855830bf3cff6a6515bb18/Final+-+Petroleum-based+Polymers+Mnfg.pdf?MOD=AJPERES. (Accessed 17 December 2017).
Katsoufis, S., 2009. Cradle-to-Gate Water Footprint Analysis of Borealis Group Polyolefin Value Chain. Master of Science Thesis. KTH, Stockholm.
Markets and Markets, 2017. Biodegradable Paper & Plastic Packaging Market by Applications (Food Packaging, Beverage Packaging, Pharmaceuticals Packaging, Personal & Home Care Packaging, and Others), Packaging Type (Plastic and Paper), & by Geography (North America, Europe, Asia-Pacific, and ROW) - Global Trends & Forecast to 2019. https://www.marketsandmarkets.com/Market-Reports/biodegradable-packaging-market-169465607.html. (Accessed 2 February 2018).
McDonough, W., Braungart, M., 2002. Cradle to Cradle: Remaking the Way We Make Things. Farrar. Straus and Giroux, New York, pp. 1–186.
Ministério da Ciência, Tecnologia, Inovações e Comunicações (MCTI), 2017. Fator Médio- Inventários Corporativos. http://www.mctic.gov.br/mctic/opencms/ciencia/SEPED/clima/textogeral/emissao_corporativos.html. (Accessed 20 November 2017).
Ministério do Meio Ambiente (MMA), 2012. Inventário Nacional de Emissões Atmosféricas por Veículos Automotores Rodoviários 2013, Ano Base 2012. Brasília, 2014.
Montagnac, J.A., Davis, C.R., Tanumihardjo, S.A., 2009. Nutritional value of cassava for use as a staple food and recent advances for improvement. Compr. Rev. Food Sci. Food Saf. 8 (3), 181–194. https://doi.org/10.1111/j.1541-4337.2009.00077.x.
Mugdal, S., Tan, A., Carreno, A.M., Prado Trigo, A., Dias, D., Pahal, S., Fischer-Kowalski, M., 2011. Analysis of the Key Contributions to Resource Efficiency. Final Report. EC/DG-ENV, vol. 116. Bio Intelligence Service S.A.S, Paris.
Plastics Europe, 2015. Plastics — the Facts 2012: an Analysis of European Plastics Production, Demand and Waste Data for 2011. Report Produced and Researched by Plastics Europe, European Plastics Converters, European Plastics Recyclers and European Association of Plastics Recycling and Recovery Organizations. Plastics Europe, Brussels.
Platts, 2015. Petrochemical Industry Conversions. https://www.platts.com/IM.Platts.Content/MethodologyReferences/ConversionTables/Images/PTSS1015_Petrochemical_Industry_Conversions_LRG.jpg. (Accessed 17 December 2017).
Raworth, K., 2017. Doughnut Economics – 7 Ways to Think like a 21st Century Economist. Chelsea Green Publishing, Vermont, USA, pp. 1–309.
Raworth, K., 2012. A Safe and Just Space for Humanity: Can We Live within the Doughnut? Oxfam Discussion Paper Oxfam, Oxford, pp. 1–26.
Ray, S., Goldar, A., Saluja, S., 2014. Feedstock for the Petrochemical Industry. Working Paper 271. Indian Council for Research on International Economic Relations (ICRIER).
Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin III, F.S., Lambin, E., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., Cynthia, A. de Wit, Hughes, T., Leeuw, S. van der, Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J., 2009. Planetary boundaries: exploring the safe operating space for humanity. Ecol. Soc. 14 (2), 32.
Steffen, W., Persson, A., Deutsch, L., Zalasiewicz, J., Williams, M., Richardson, K., Crumley, C., Crutzen, P., Folke, C., Gordon, L., Molina, M., Ramanathan, V., Rockström, J., Scheffer, M., Schellnhuber, H.J., Svedin, U., 2011. The Anthropocene: from global change to planetary stewardship. Ambio 40, 739–761.
Steffen, W., Richardson, k, Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., Sörlin, S., 2015. Planetary Boundaries: guiding human development on a changing planet. Science 347, 6223.
Stockholm Resilience Centre (SRC), 2016. High Level Group. Innovation Policy Management. Working Group on Resilience Management and the Circular Economy. Report through Resilience Thinking towards Sustainability and Innovation – Recommendations for Policy Makers in the EU, Brussels.
Takahashi, M., Guerini, V.L., 1998. Espaçamento para a cultura da Mandioca. Braz. Arch. Biol. Technol. 41, 4. https://doi.org/10.1590/S1516-89131998000400014.
Thompson, R.C., Moore, C.J., vom Saal, F.S., Swan, S.H., 2009. Plastics, the environment and human health: current consensus and future trends. Philos. Trans. R. Soc. Lond. Ser. B Biol. Sci. 364 (1526), 2153–2166.
United Nations (UN), 1987. Report of the World Commission on Environment and Development: Our Common Future (Brundtland Report). United Nations, New York, pp. 20–51.
United Nations Environment (UNEP), 2015. Biodegradable Plastics and Marine Litter. Misconceptions, Concerns and Impacts on Marine Environments. United Nations Environment Programme, Nairobi, p. 32.
United Nations Environment Programme (UNEP), 2014. Valuing Plastics: the Business Case for Measuring. Managing and Disclosing Plastic Use in the Consumer Goods Industry, Nairobi.
World Economic Forum, 2017. The New Plastics Economy Catalyzing Action. http://www3.weforum.org/docs/WEF_NEWPLASTICSECONOMY_2017.pdf. (Accessed 14 March 2017).
World Packaging Organization, 2009. Market Statistics and Future Trends in Global Packaging, Naperville, IL.
Worldatlas, 2017. Top Cassava Producing Countries in the World. http://www.worldatlas.com/articles/top-cassava-producing-countries-in-the-world.html. (Accessed 12 October 2017).
Worldwatch Institute, 2015. Global Plastic Production Rises, Recycling Lags. http://vitalsigns.worldwatch.org/sites/default/files/vital_signs_trend_plastic_full_pdf.pdf. (Accessed 3 March 2017).